Modeling the spectrum of a luminaire including a dichroic filter by spectral ray tracing

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Abstract

Ray tracing is a useful tool in the optical design of luminaires. Usually simulations are performed at one wavelength. However, in some luminaires optical components are incorporated to alter the spectrum of the light source. In a retail environment, luminaires equipped with a dichroic filter are commonly used to enhance the attractiveness of products. In this paper, spectral ray tracing is used to model the spectral radiant intensity distribution of such a luminaire. A geometric model of the luminaire, the spectral distribution of the lamp and the spectral scattering and transmission properties of the reflector and the filter are used as input parameters. The spectral radiant intensity at several emission angles as modeled by spectral ray tracing is compared with the experimentally determined values. A very good agreement is found. Furthermore, ray tracing simulations reveal detailed information about the effect of light recycling in the luminaire on the emission spectrum.

Keywords: spectral ray tracing, retail lighting, optical modeling

Introduction

Monte Carlo ray tracing is frequently used as a tool to validate the optical performance of optical systems and virtual prototypes of luminaires [1,2,3]. In many cases, the optical properties of the materials in the design are more or less wavelength independent, allowing the ray tracing calculations to be performed at one wavelength in order to strongly reduce the simulation time. However, for some special purpose luminaires, the spectrum emitted by the light source is, by design, altered by one or several optical components of the luminaire. Typically in retail lighting, both colored filters combined with a classic light source, and spectrally designed solid state lighting sources are implemented. It is well documented that consumer acceptance of a food product strongly depends on the visual appearance of the product, and that the perceived color of the product is one of the most important visual cues [4].

Particularly, consumers perceive fresh meat and some types of dark colored fresh fish as more appealing when illuminated with a radiant spectrum dominated by red light [5,6]. A computer model of the optical behavior of a filter based luminaire for the illumination of food products needs to take into account the combined influence of the light source, the optics and the filter, on the spectrum of the light emitted by the luminaire. Therefore, a ray tracing model of such a device needs to account for the entire visual spectrum of the light source. In this paper a luminaire for retail lighting of meat products (Flexio from LUNOO NV) equipped with a Philips SDW-T 100W lamp and a dichroic filter is discussed. The filter is especially designed to be used in combination with the SDW-T lamp for the illumination of meat products. An interference filter has the advantage over a color filter based on light absorption that almost no light is lost in the filter. However, a typical disadvantage of an such a filter is that the spectral transmission depends on the angle of incidence. This results in the spectrum of the light emitted by the luminaire to be function of the emission angle. At small emission angles this effect is not visible but at larger angles a color shift becomes visually apparent. In this work, the spectral radiant intensity of the luminaire is experimentally determined with a goniophotometer setup at several emission angles and calculated at the same emission angles by Monte Carlo ray tracing. The simulation takes into account the spectral surface scattering properties of the reflector material, and the dependency of the spectral reflection and transmission properties of the interference filter on the angle of incidence. The discharge lamp is modeled with a relatively simple geometric model. Additionally the effect of light recycling by the reflector of light initially reflected by the interference filter is investigated.

Experimental set-up and measurements

The surface of the reflector material scatters light in a wide angular pattern around the specular direction. The angular scattering properties need to be modeled accurately to enable realistic ray tracing simulations [7,8]. Surface scattering properties are mathematically modeled by the Bidirectional Reflectance Distribution Function (BRDF), which is defined as the ratio of the infinitesimal radiance $dL_{e,s}$ of the irradiated sample in a particular viewing direction, to the infinitesimal irradiance $dE_{e,i}$ on the sample by a collimated beam from a particular direction (equation 1). The index *e* indicates that this is a radiometric and not a photometric property, while the indices *i* and *s* indicate incident and scattered light respectively. Because surface scattering can be wavelength dependent, the BRDF is a function of 5 variables: θ_s and ϕ_s are spherical coordinates defining a particular scatter direction relative to the surface normal, θ_i

and ϕ_i are spherical coordinates defining the direction of the incident beam, and λ is the wavelength (Equation (1)).

$$BRDF(\theta_i,\phi_i,\theta_s,\phi_s,\lambda) = \frac{dL_{e,s}(\theta_i,\phi_i,\theta_s,\phi_s,\lambda)}{dE_{e,i}(\theta_i,\phi_i,\lambda)}[\frac{1}{sr}] \tag{1}$$

Under particular circumstances the generic expression for the BRDF (Equation (1)) is transformed into a practical expression (Equation (2)), $\Phi_{e,s}$ and $\Phi_{e,i}$ represent the scattered and incident radiant flux, respectively, Ω_s being the solid angle subtended by the detector, and θ_s the angle between the surface normal and the scatter direction [9].

$$BRDF(\theta_i,\phi_i,\theta_s,\phi_s,\lambda) = \frac{\Phi_{e,s}}{\Phi_{e,i}\Omega_s\,|\cos(\theta_s)|}[\frac{1}{sr}] \tag{2}$$

Spectrally resolved BRDF measurements are carried out with an in house designed and constructed gonioradiometer [10]. In Figure 1 the BRDF of the reflector material is shown as a function of scatter angle for a number of incidence angles. The surface scatter data are shown at a wavelength of 555nm. The spectral behaviour of the BRDF for a particular angle of incidence, i.e., 53°, and scatter direction 75° to surface normal, is depicted in Figure 2. For all incidence angles and all scatter angles, the BRDF exhibits small amplitude oscillations. The interference filter used in the luminaire consists of a number of thin transparent layers with different indices of refraction. The mulitlayer uses constructive and destructive interference to transmit light at certain wavelengths at certain angles of incidence and to reflect the same wavelengths at other angles of incidence. The interference filter is supported by a transparant glass plate with negligible absorption and scattering. Absorption in the multilayer itself is of the order of magnitude of 3% while the scattering is negligible [10]. The filter exhibits only regular transmission and specular reflection which are characterized by the transmission and reflection coefficients (Equation (3) and (4)). The reflection and transmission coefficient are experimentally determined with the BRDF measurement set up.

$$T(\lambda,\theta) = \frac{\Phi_{e,t}}{\Phi_{e,i}} \tag{3}$$

$$R(\lambda,\theta) = \frac{\Phi_{e,r}}{\Phi_{e,i}} \tag{4}$$

In Equation (3) and (4) the indices i,t and r respectively refer to the incident, transmitted and reflected flux. The index e is used to indicate radiant flux (Watt), not luminous flux (lumen). The transmission and reflection coefficients are measured as a function of wavelength for a number of incidence angles. In Figure 3, the measured regular transmission coefficient is shown for three incidence angles. Notice that the transmission coefficient as a function of wavelength depends significantly on the incidence angle.

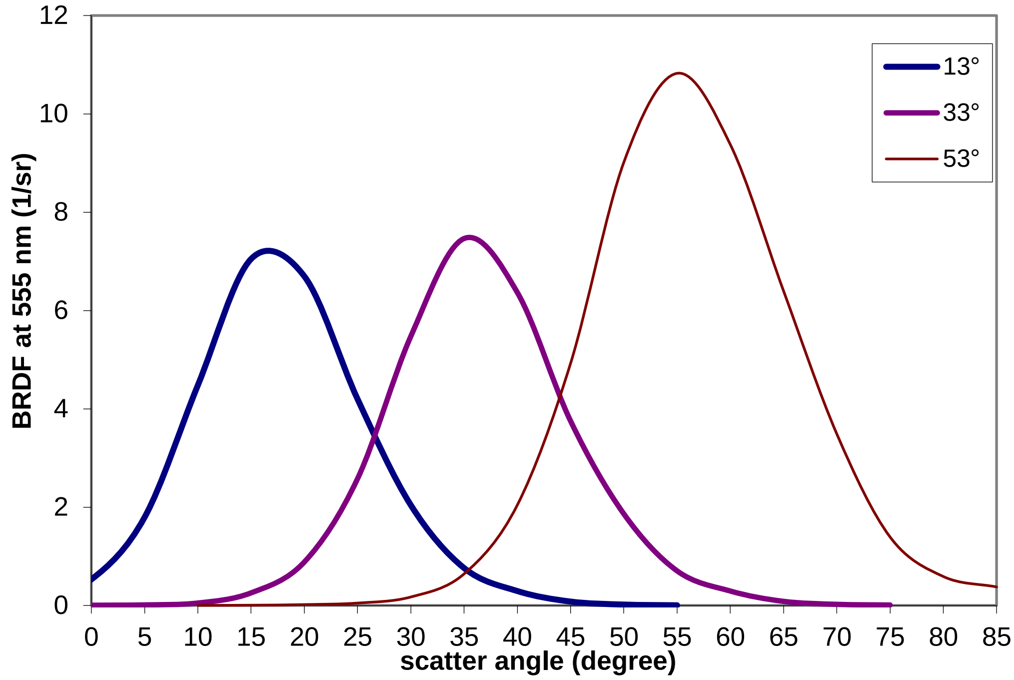


Fig. 1. BRDF of the reflector material as a function of scatter angle at a wavelength of 555nm at an incident angle of: 13°, 33° and 53°.

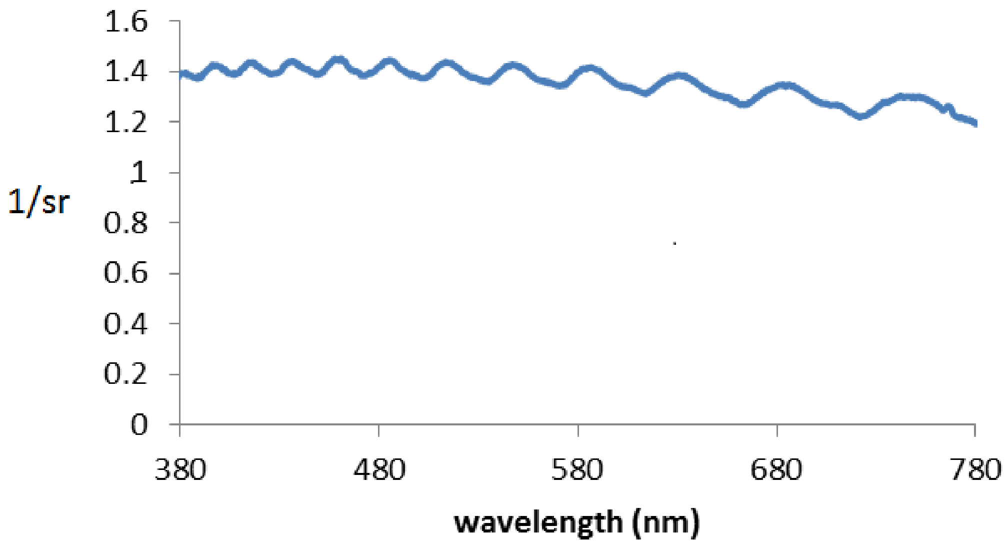


Fig. 2. BRDF (in units 1/sr) of the reflector material as a function of wavelength at an angle of incidence of 53 degree and scatter direction 75 degree to the surface normal.

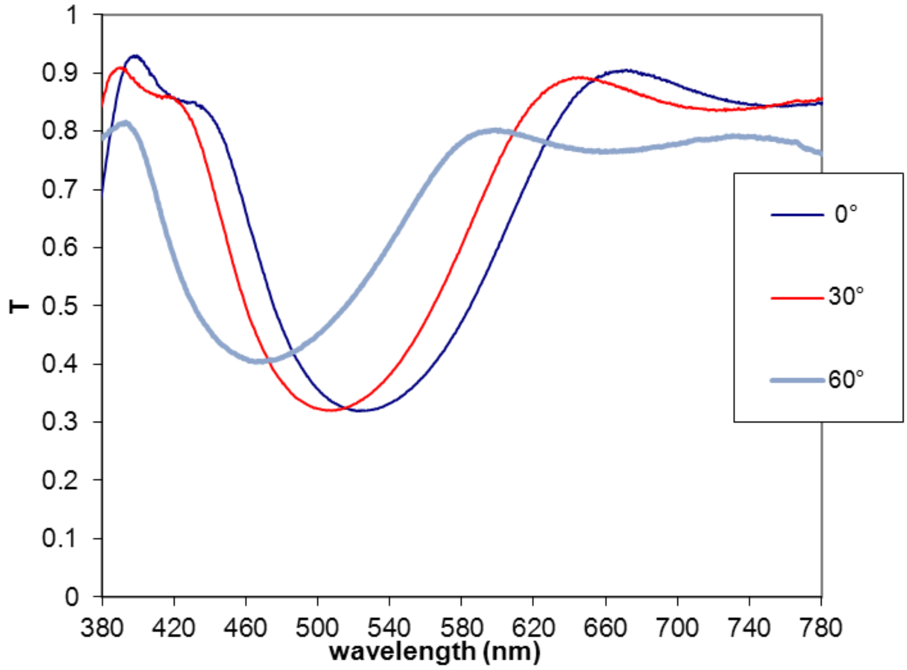


Fig. 3. Transmission coefficient of the interference filter as a function of wavelength for three angles of incidence.

To measure the emission spectrum of the luminaire as a function of emission angle the luminaire is mounted in a CIE type 1 goniophotometer [11] which can rotate the lighting fixture around a horizontal and vertical axis. The light is captured by a Topcom 100 camera positioned in the far field at a distance of 8.72m from the luminaire. The captured light is transferred by an optical fiber to an Oriel Multispec spectrograph. Because the detection system is positioned in the far field and the complete lighting fixture is located within the field of view, the recorded spectrum is interpreted as the spectral radiant intensity spectrum of the luminaire. The emission spectrum of the naked SDW-T lamp is measured by the same procedure. The spectrum of the lamp, in arbitrary units, normalized to one is shown in Figure 4.

Spectral Monte Carlo ray tracing

A commercial software package, TracePro® from Lambda Research Corporation, is implemented to perform the Monte Carlo ray tracing. The geometry of the luminaire is modeled in the software package using CAD-files of the reflector, as supplied by the manufacturer, and a generic model of an SDW-T lamp, as available in the software package's library. The geometric model of the luminaire is shown in Figure 5. The surface of the cylindrical gas discharge tube in the lamp is considered to be the light source and is modeled as a Lambertian surface source. This relatively simple source model is acceptable because the source is small and positioned at a relatively large distance from the reflector. Furthermore the emission spectrum of the lamp does not vary strongly with emission angle. If the latter was the case a

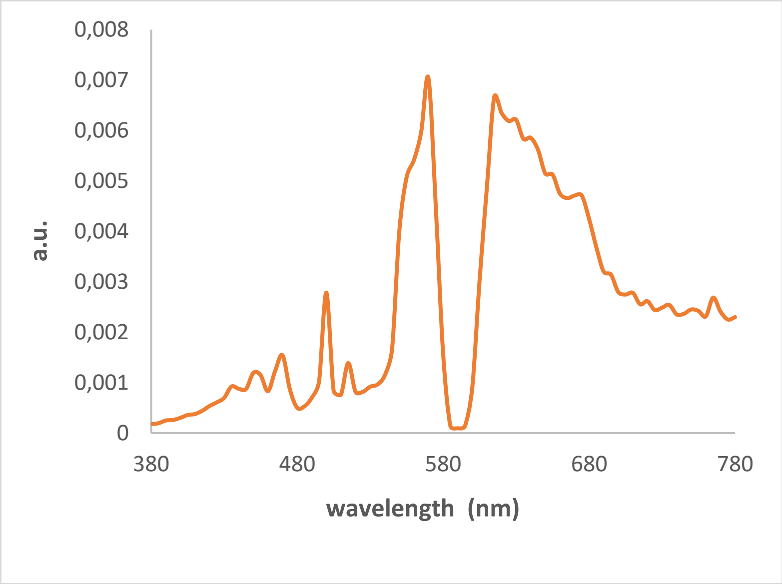


Fig. 4. Normalized measured spectrum of the SDW-T lamp, expressed in arbitrary units.

much more advanced spectral source model based on spectral ray files would be required [12,13]. The surface scatter data for the reflector material and the transmission and reflection coefficient of the interference filter are transferred into the appropriate format and imported in the ray tracing software. The scatter data are somewhat simplified as it is impractical to include the small oscillations that are slightly different for each angle of incidence. Therefore the BRDF is assumed to be constant between 380nm and 570nm, and to decrease linearly between 570nm and 780nm in such a way that the total integrated scatter (TIS) agrees with the experimental value. To model the detector, a disk shaped target with diameter 3mm (i.e. the same dimensions as the entrance aperture of the Topcom 100 camera) is created in the model and positioned at a distance of 8.72m from the luminaire. Because of the small dimensions of the ray tracing target and the large distance to the light source, the probability of a random ray hitting the target is extremely small, making classic source to target ray tracing impractical. Therefore a technique frequently applied in computer graphics, reverse ray tracing, is implemented [14]. In reverse ray tracing rays are traced backwards through the optical system, i.e. from target to source, and a history of the events encountered by the rays (e.g. Fresnel reflection, surface scatter, etc…) is logged. If and when a ray impinges on the source, a flux is assigned to it according to the emission properties of the source. From this emitted flux, and taking into account the complete history of the ray, the flux observed at the target is calculated. To model the emission spectrum of the SDW-T lamp, 1 million rays per wavelength are traced at 81 wavelengths in the range 380nm – 780nm with 5nm increments. The relative radiant flux at each wavelength is weighted according to the emission spectrum of the discharge lamp.

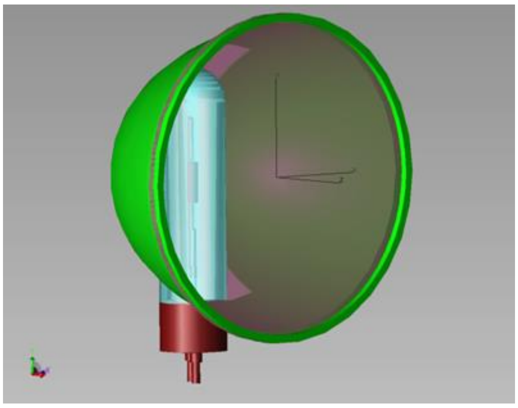


Fig. 5. *Model of the luminaire used in the ray tracing simulations.*

Results and discussion

Both the measured and simulated spectra are normalized such that the integrated spectra equal unity. The spectra found by reverse ray tracing can be deconstructed in component spectra corresponding to light taking different paths through the optics [15]. Three component spectra are considered: the direct light contribution (i.e. light that travels directly from source to target, through the filter), light that is scattered once by the reflector and afterwards transmitted through the filter before being detected, and light that is scattered more than once by the reflector before passing through the filter and reaching the target. In Figure 6,7 and 8, a comparison is made between the measured and calculated spectra, expressed in arbitrary units, at 0, 30 and 60 degree emission angle. A good agreement is found between the simulated spectrum and the measured spectrum in all three situations. From the simulations, it becomes clear that the relative contribution of the three component spectra to the entire spectrum changes as a function of emission angle. The spectrum emitted at 0 degree is dominated by light that is scattered once by the reflector. The component corresponding to light that is scattered several times by the reflector material is larger than the direct light contribution. At an emission angle of 30 degree the direct light contribution has become larger than the multiple scatter contribution, but the spectrum is still dominated by light that is scattered once by the reflector. At an emission angle of 60 degree the line of sight between the detector and the gas discharge tube is blocked by the reflector, and the direct light contribution is zero. However, part of the inner side of the reflector is still visible from the detector position and light reaches the detector after being scattered at least once by the reflector. From the ray tracing simulations it becomes clear that the spectrum is now dominated by light that is scattered several times by the reflector surface.

The chromaticity of light stimuli and the chromaticity difference of light sources is, as recommended by the CIE, preferably expressed in the CIE (u',v') chromaticity diagram [16].

The chromaticity difference between two light sources, A and B, is expressed by Equation (5).

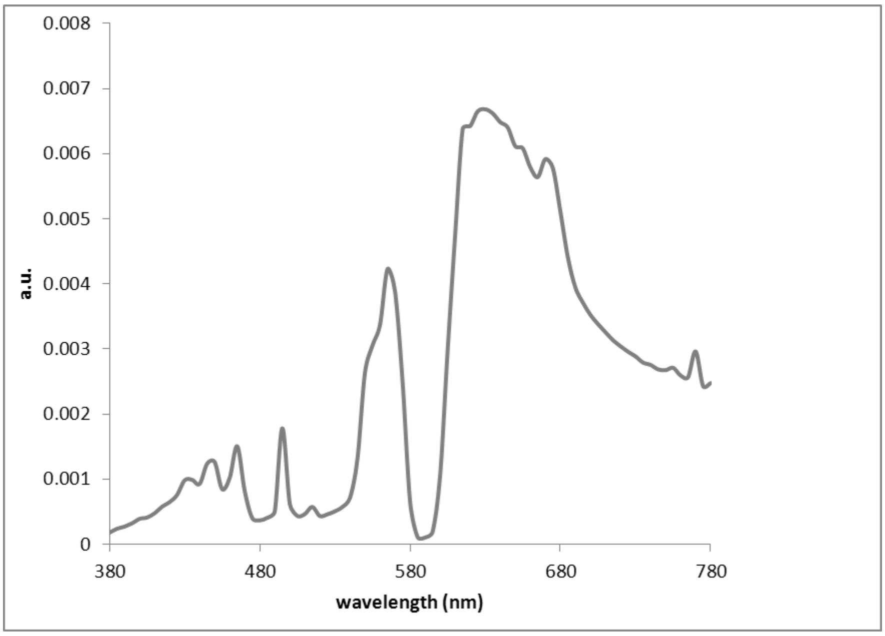
$$\Delta_{(u',v')} = \sqrt{(u'_A - u'_B)^2 + (v'_A - v'_B)^2} \quad (5)$$

The Just Noticeable Difference in chromaticity (at 50% probability) corresponds to a difference in chromaticity coordinates of 0.0013. In Table 1, the (u',v') chromaticity coordinates calculated from the measured and simulated spectra and the chromaticity difference between simulation and experiment are shown. Notice that the chromaticity difference increases with emission angle. This is probably caused by the statistical noise inherent to the ray tracing procedure. In each reverse ray tracing session, 1 million rays per wavelength are launched but because of the different geometry the number of rays that actually reaches the light source is different. At emission angle zero, typically 29% of the rays arrive at the source, but at 30 degree emission, only 19% of the rays hit the light source and at 60 degree emission, less than 1% of the rays contribute to the simulated spectrum. As the number of rays that contribute to a simulated spectrum decreases with emission angle the noise on the simulated spectra increases with emission angle.

Table 1. CIE (u',v') chromaticity coordinates calculated from the measured and simulated spectra. The difference in chromaticity between simulation and experiment increases with emission angle.

emission angle	experiment	simulation	$\Delta_{(u',v')}$
0 degree	u'=0.3125 v'=0.5088	u'=0.3119 v'=0.5086	0.0006
30 degree	u'=0.3097 v'=0.5196	u'=0.3163 v'=0.5191	0.0066
60 degree	u'=0.1982 v'=0.5360	u'=0.2087 v'=0.5365	0.0105

It is interesting to have a look at the impact of the recycling of light on the spectrum. Light emitted by the source is back reflected by the interference filter to the reflector. At the reflector surface it scatters at least once, impinges on the filter again, is transmitted, and contributes to the spectral radiant intensity of the luminaire. In order to investigate if light recycling has an impact on the emission spectrum of the luminaire, the ray tracing model is adapted. In the model the interference filter is removed from the luminaire and repositioned at a large distance (8m) from the reflector but parallel with its original configuration. In this configuration the line of sight from the detector, through the interference filter, to the reflector and the lamp is not altered but light that is reflected by the filter will not reach the reflector and disappear from the simulation, thus eliminating light recycling. In Figure 9 the simulated emission spectra at 0 degree emission angle are compared. In the modified geometry, the contribution to the spectrum of light that is scattered multiple times is of the same order of magnitude as the direct light component while in the classic luminaire geometry the multiple scatter component dominates the direct light component in the wavelength range 540-650nm. This suggest a difference in chromaticity of the light between both cases. It should be noted that, since the properties of the reflector material are practically independent of wavelength, the spectrum without light recycling is the spectrum that would be observed while viewing the light source through the interference filter without any other optics present. In Table 2 the CIE (u',v') chromaticity coordinates of the experimentally observed spectrum, the simulated spectrum, the simulated spectrum without recycling and the spectrum obtained by multiplying the spectrum of the lamp with the transmission coefficient of the dichroic filter are listed. Also the chromaticity difference between the measured spectrum and the other spectra is shown. From the table it is clear that the chromaticity of the light emitted by the luminaire cannot be found by simply multiplying the emission spectrum of the lamp with the transmission coefficient of the filter, this despite the fact that the scattering properties of the reflector are practically independent of wavelength. The simulations show that light recycling by the optics of the luminaire has a significant influence on the spectrum and chromaticity of the light. The simulated spectra at 30 degree and 60 degree emission angle have more statistical noise and thus the chromaticity corresponding to these spectra is less in agreement with the experimental data (Table 1). The spectra are shown in Figure 10 and Figure 11. At emission angle 30 degree, the spectrum without light recycling shows a reduction of the contribution of light that is scattered several times by the reflector surface. However, the overall shape of the spectrum and the relative contribution of each of the components is not altered significantly relative to the spectrum shown in Figure 7. In this particular situation the effect of light recycling is relatively small. The situation at 60 degree emission angle is quite different (Figure 11) and the spectrum excluding light recycling is completely different. In this case the line of sight from detector to the gas discharge tube, the actual light source, is blocked by the reflector and the spectrum with light recycling is strongly dominated by light that is scattered several times. Excluding light recycling causes the single scatter contribution and the multiple scatter contribution to be of equal importance, which results in a completely different spectrum.



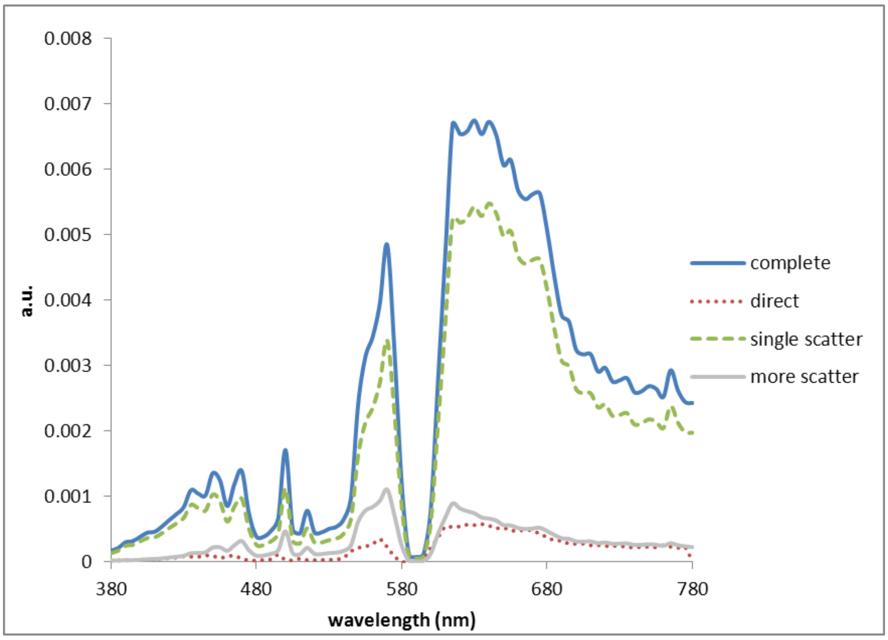


Fig. 6. Measured (top) and simulated spectrum (bottom) of light emitted at emission angle 0 degree and captured at a distance of 8.72m from the luminaire. Light that is scattered once dominates the spectrum and the multiple scatter component is more important than the direct light contribution.

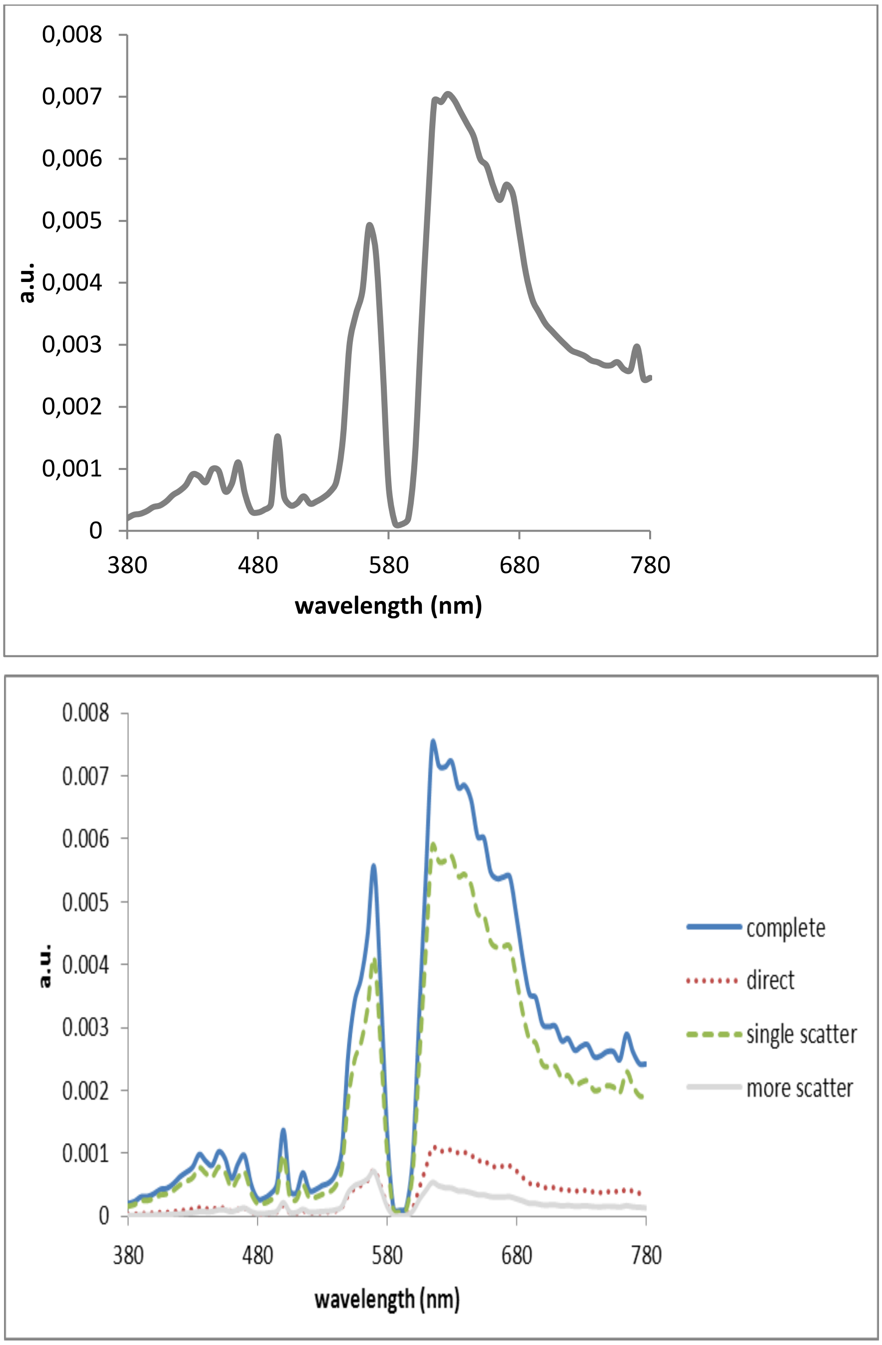


Fig. 7. Measured (top) and ray traced spectrum (bottom) of light emitted at emission angle of 30° and captured at a distance of 8.72m. The intensity spectrum is dominated by light that is scattered once and the direct light contribution is more important than the multiple scatter component.

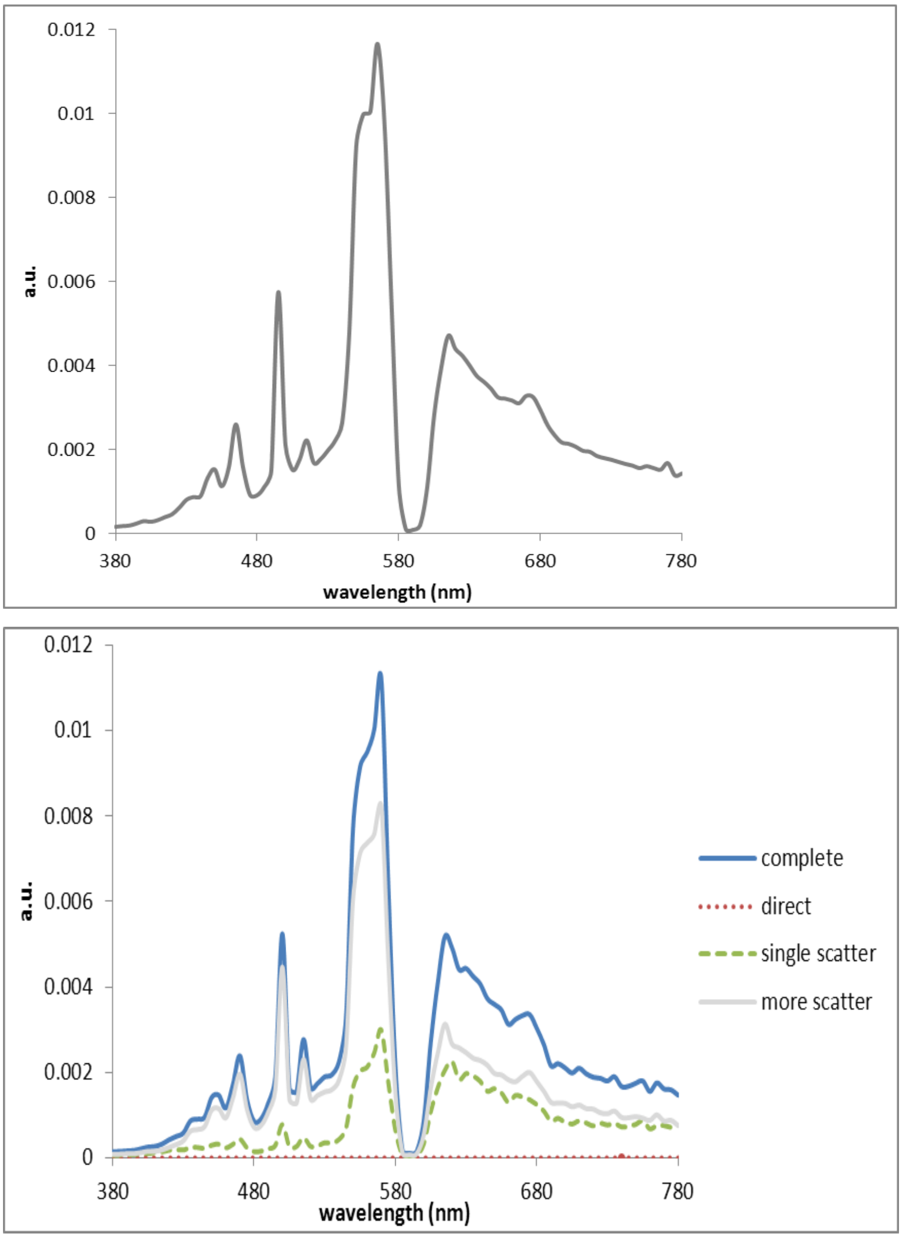


Fig. 8. Experimentally determined (top) and simulated spectrum (bottom) of light emitted at an emission angle of 60 degree and captured at a distance of 8.72m from the luminaire. The spectrum is dominated by light that reaches the detector after multiple scattering events. There is no direct light contribution.

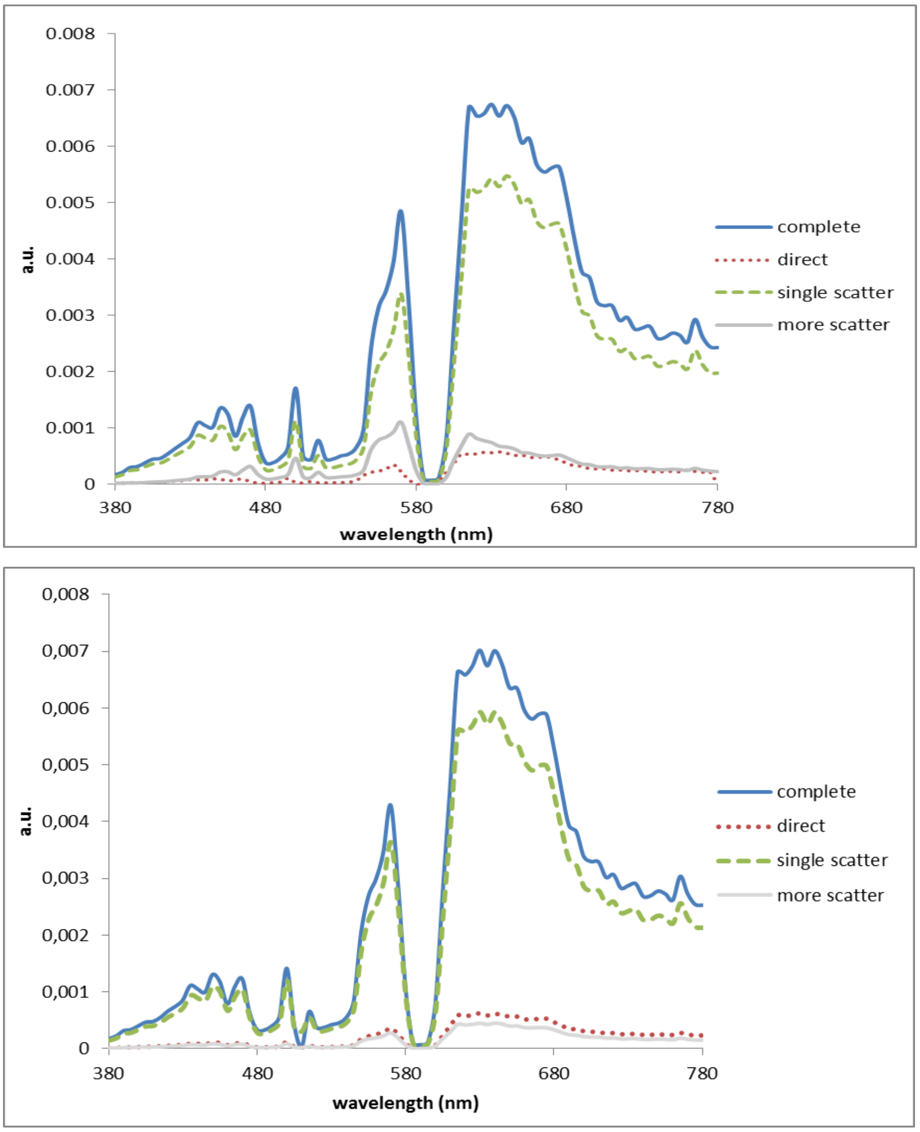


Fig. 9. Emission spectra at 0 degree emission angle found from ray tracing calculations of the luminaire (top) and in the modified geometry excluding light recycling (bottom). Notice that in the situation excluding light recycling, the contribution of the more scatter component is significantly reduced.

Table 2. CIE (u’,v’) chromaticity coordinates corresponding to the experimental spectrum, the simulated spectrum of the luminaire, the simulated spectrum excluding light recycling and the spectrum found by multiplying the original lamp spectrum with the 0 degree transmission coefficient of the interference filter. Also shown are the differences between the chromaticity of the measured light and the chromaticity corresponding to the calculated spectra.

	Measured spectrum	Simulated spectrum	Simulated spectrum without recycling	(lamp spectrum) x (transmission coefficient)
Chromaticity	u’=0.3125 v’=0.5088	u’=0.3119 v’=0.5086	u’=0.3271 v’=0.5056	u’=0.3289 v’=0.5058
Chromaticity difference with measured spectrum		$\Delta_{(u',v')} = 0.0006$	$\Delta_{(u',v')} = 0.0150$	$\Delta_{(u',v')} = 0.0166$

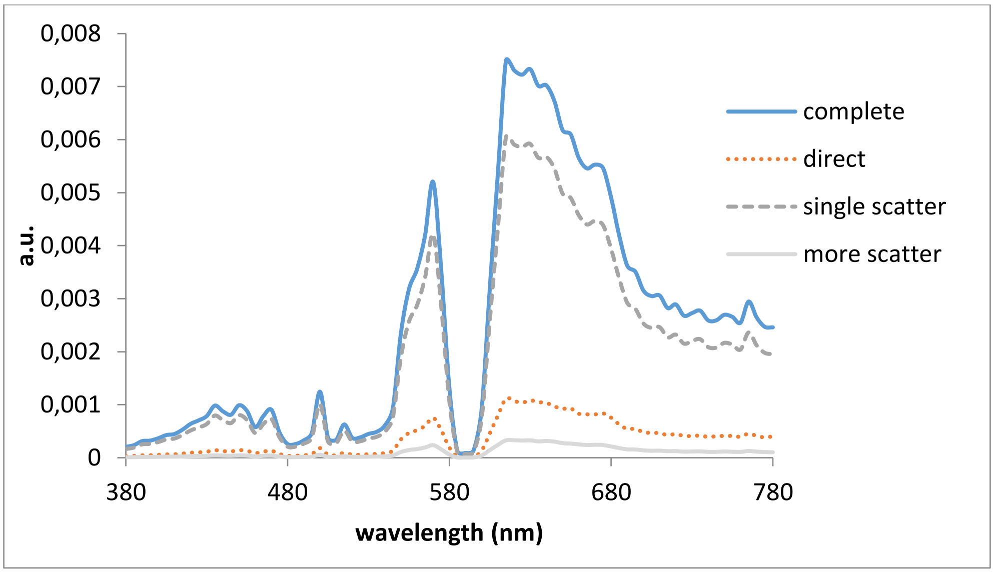


Fig. 10. Simulated spectrum of the emitted light at 30 degree emission angle without light recycling.

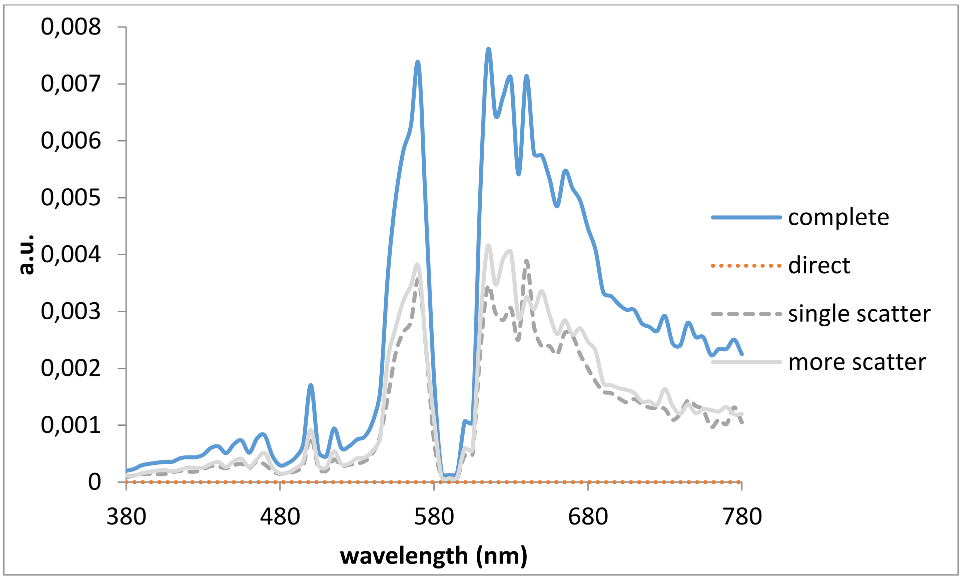


Fig. 11. Simulated emission spectrum, excluding light recycling, at emission angle 60 degree

Conclusion

Spectral Monte Carlo ray tracing can be used to accurately model the angle dependent spectrum of luminaires containing spectrally non-neutral optical components such as interference filters. The spectra resulting from computer simulations correspond very well to the measurements and additionally yield interesting information about how the spectrum is composed of light taking different paths in the luminaire and how this composition changes with the emission angle. The phenomenon of light recycling in the luminaire is investigated by repeating the computer simulations with a slightly altered geometry that excludes this phenomenon. It is found that light recycling is of significant importance to explain the spectral radiant intensity and the chromaticity of the emitted light. This type of modeling contributes to a better understanding of unwanted spectral shifts in luminaires and additionally provides a useful tool for the optical design of lighting systems.

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